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Co-optimisation of send and receive coils

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Abstract

Magnetic particle imaging exploits the nonlinear magnetization behaviour of iron oxide nanoparticles, by modulating the magnetic flux density of those particles. This modulation is achieved by creating time-varying magnetic fields using a drive coil. The generated signal is picked up with a receive coil. In order to minimize mutual influence, those coils need to be optimized. The decision process for an optimal combination of drive and focus field coil and the receive coil is described with respect to the signal chain and power consumption of the scanner. It is shown that the advantages of longer coils result in a linear increase of the power loss in the scanner, while the obtained sensitivity no longer increases relevantly. Based on this analysis a coil with favourable cost-benefit ratio can be chosen.

I Introduction

In magnetic particle imaging (MPI) the concentration of (superparamagnetic) iron oxide nanoparticles (SPION) can be spatially resolved. The method is based on the nonlinear magnetisation behaviour of those SPIONs and exploits this by exciting them with a time-varying magnetic field of sufficient amplitude. Previously a scanner system featuring a permanent magnet based field free line (FFL) was presented [1]. One drawback of the current system is its small field of view. To avoid the stimulation of peripheral nerves and the warming of tissue it is not possible to simply increase the drive field (DF) amplitude higher than the current 20 mT at the frequency of 25 kHz. Therefore, an additional focus field (FF) of 80 mT should be generated, that moves the FFL slowly at a chosen frequency of 100 Hz.

The current aim is to generate this field using the same coil with a diameter of 56.5 mm that also generates the DF, since previous simulations on alternative approaches show poorer power loss properties and a lower sensitivity of the receive coil. In order to decide on the parameters of this combined coil, the circuit or signal chain needs to be analysed, as the coil and the circuit mutually influence each other. So, design decisions concerning one component inevitably force adjustments of the other components. This paper aims to show the decision on an optimal single layered send coil for the system with respect to the receive coil.

II Material and methods

The gradient field of the components that creates the FFL (in the r/h-plane) solely consists of magnetic field components that point in z-direction. Therefore, the coil for generating the magnetic field that moves the FFL can be built as a solenoid, which gives some advantages regarding constructional effort and power consumption when compared to approaches with multiple coils. To drive this coil with the necessary current generating the desired fields, the combined coil is included in a circuit that features the signal chains for the drive- and focus-field (see Fig. 1).

The send chain on the drive field side shows an often used and well-tested approach consisting of a power amplifier, a bandpass to attenuate all frequencies except the

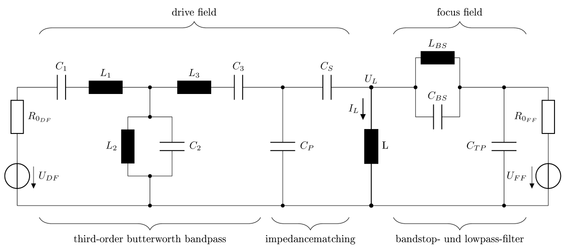

Figure 1: Signal chain for drive (left) and focus (right) field. The left-hand side shows the drive field source, the bandpass and impedance matching. On the right-hand side, the bandstop filter is included to protect the focus field source.

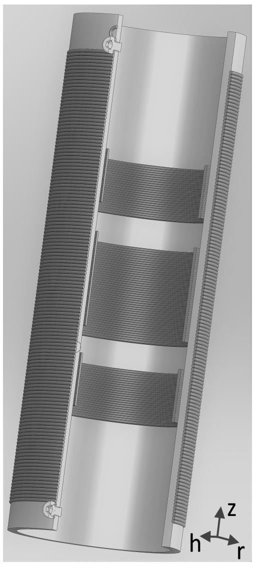

Figure 2: Overview of the simulated coil design. The outer coil is the combined drive and focus field coil while the gradiometric coil with its three winding blocks lies inside.

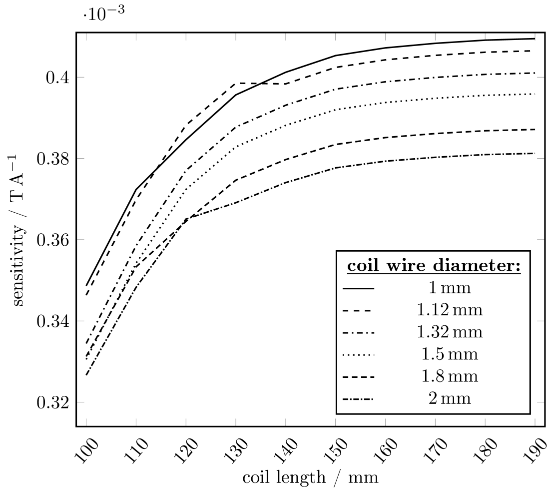

Figure 3: Sensitivity of the receive coil.

desired drive frequency and the impedance matching to maximize the power transfer from source to coil [2].

The right side shows the source for the focus field and a combination of a notch and a low pass filter. This filter acts as source protection, as it reduces the voltage that is fed through from the DF source. The inductance for this filter will be built as air cored toroid and is simulated using a script based on [3] to calculate an optimal toroid for the needed inductance.

This filter prevents the source from being damaged and at the same time prevents deterioration of the signal quality delivered by the source, because internal processes should not be influenced by the low external voltage. An equivalent protection for DF source is given by the impedance matching and the bandpass filter, as the low frequency voltage from the focus field source is efficiently blocked by its capacitors.

The shown circuit was analysed manually by building transfer functions, especially from DF to FF source and from both sources to the field generating inductor. Using the superposition principle, the circuit can be analysed for each source independently. Additionally, a simulation in MATLAB (R2019b, The MathWorks, Inc.) allows a fast analysis of the send chain features with varying parameters.

Important parameters that influence design choices include the total power loss of the system, separated into the DF and FF path, which can be separated into the power loss in the coil and the notch filter respectively. The total power loss is limited by the maximal cooling capacity of the system and the power that the sources can deliver.

In order to optimize the receive coil for the system, both coils were simulated for different coil lengths and wire diameters, using finite element analysis (COMSOL Multiphysics 5.4, COMSOL Inc.) to analyse the coil parameters, mutual influences and especially the sensitivity of the receive part. To reduce the influence of the ambient field, the receive coil was simulated as a gradiometric coil with an optimal length-to-radius ratio of 1.29 for the central windings, depending on its chosen diameter of 47 mm, which should be used for preclinical imaging [4]. Within some distance matching compensation windings with an inversed current direction are placed on each side of the central part (see Fig. 2).

III Results and discussion

Increasing the length of the send coil shows quite some advantages. The homogeneity along all axis increases. Therefore, the compensation windings of the receive coil can be placed further apart minimizing the mutual induction between both parts.

On the other hand, an elongated coil shows a higher inductivity and resistance, a higher voltage drops across

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the component, and the power consumption increases. Due to the higher voltage, the damping of the bandstop filter needs to increase as well, to reduce the voltage that reaches the FF source to the same level. Subsequently, the inductance and quality factor of the toroid inside this filter needs to be increased too. Also, as the coil and toroid basically build a current divider, the inductance of the toroid needs to be higher than the one of the coil to maximize the current through the coil. Consequently, more power is lost inside the notch filter.

The coil was also analysed for different wire diameters between 1 mm and 2 mm. Due to the use of enamelled copper wire at a diameter of 1 mm the skin depth of the material almost corresponds to the wire radius, and therefore everywhere inside the wire the same conditions apply. Smaller wires would have a much larger resistance and therefore the power consumption would increase. A bigger cross-sectional area reduces the needed power, but due to the lower winding density the homogeneity of the magnetic field decreases.

The decisive parameter for choosing a coil is the receive coil sensitivity. This parameter decreases with higher wire diameter and therefore a DF coil with a wire diameter of 1 mm is chosen. The sensitivity increases with longer coils, but with a decreasing slope (see Fig. 3).

For coils longer than 150 mm the gain of sensitivity is below half a percentage point. But in contrast, for each step the total power of the system increases by about 5 % or 100 W.

IV Conclusions

To obtain maximum sensitivity while not unreasonably increasing power requirements, a 150 mm solenoid coil with 1 mm wire diameter should be selected. The total power consumption of the system is then about 2.1 kW. Further optimization on the distance between central and compensation windings should be carried out to minimize the induced voltage in the receive coil. Due to the high power loss in both coil and toroid, options to cool those components are under development before the system can be implemented.

Author's Statement

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